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Remote Attenuation System Target Diagnostics National Ignition Facility Lawrence Livermore National Laboratory

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REMOTE ATTENUATION SYSTEM
TARGET DIAGNOSTICS
NATIONAL IGNITION FACILITY
LAWRENCE LIVERMORE NATIONAL LABORATORY

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APRIL 17, 2014

Contents

1. EXECUTIVE SUMMARY

This document describes the systems engineering process and results performed for the Remote Attenuation System (RAS) to be implemented on the target diagnostics of the National Ignition Facility at the Lawrence Livermore National Laboratory. The mission of operational cost reduction is discussed in Section 2, along with the identification of stakeholders and their expectations of what the new system be. In Section 3, we identify the existing reference system, that which needs to be replaced or upgraded. Also defined is the boundary of the new system to be designed.

Section 4 highlights the key system drivers and constraints, and Section 5 details a number of operational scenarios and use cases that will be used to inform system requirements. In Section 6, we present a Quality Function Deployment matrix that then drives a number of implementation concepts. A trade study is used to identify the concept that best meets expectations and constraints.

In Section 7, we propose a system architecture and define requirements. We further evaluate the market for off-the-shelf solutions that fit our proposed system architecture. In Sections 8 and 9, we present the proposed systems impact or our organization and perform a risk assessment.

2. MISSION DESCRIPTION

The mission is to reduce the lifetime costs of running target diagnostics at the National Ignition Facility (NIF) with respect to signal level control and recording. The current system requires local human intervention to select, install, and remove discrete fixed attenuator components. This system is expensive to operate. The proposed Remote Attenuation System (RAS) will reduce operational costs, reduce setup time, improve reliability, and increase system lifecycle.

2.1 Active Stakeholders

These active stakeholders interact directly with the RAS after installation and commissioning of the system.

2.1.1.1 Responsible Scientists (RS) - Multiple

There are multiple RS's depending on the diagnostic that the RAS will be installed on. The responsible scientist owns the scientific out of a diagnostic and expects the RAS to operate reliably, consistently, and can be calibrated so as not to introduce significant errors into analyzed shot data results.

2.1.1.2 Responsible Systems Engineer (RSE)

There are multiple RSE's depending on the diagnostic that the RAS will be installed on. The RSE owns the system and has the same expectations as the RS, that the RAS to operate reliably, consistently, and can be calibrated so as not to introduce significant errors into analyzed shot data results.

2.1.1.3 National Security Technologies (NSTec)

NSTec personnel will be tasked with routine calibration of the RAS. Any changes to the existing calibrations procedures must be clarified. Training and equipment may also need to be provided, depending on RAS architecture.

2.1.1.4 NIF Electrical Field Technicians

Routine calibration and maintenance will require technician support for periodic installation, removal, and installation qualification checks. The techs will need to be briefed and trained.

2.1.1.5 NIF Target Diagnostic Coordinator and Operators (TDC and TDO)

The TDC/TDO is responsible for shot setup and operations. He needs to be made aware of any changes to the diagnostic that may impact shot setups and operations including failure modes. There are multiple TDC's depending on shift.

2.1.1.6 Diagnostic Signal Path

All scope-based diagnostic systems at NIF record an electrical time-varying voltage signal. This signal is generated at the detection end of the diagnostic by transduction from other forms of energy, typically X-ray, optical, gamma, or neutron. In electrical form, the signal travels via transmission lines, from the detection end of the diagnostic to the scopes. In order to effect attenuation to the electrical signal, the transmission line must be broken such that attenuation circuits can bin inserted.

2.1.1.7 The NIF Information Command and Control Systems (ICCS)

The NIF control system will interfaces with CMT to obtain shot setup requests and then implements those requests via electronic control of the RAS.

2.1.1.8 Configuration Management Tool (CMT)

CMT is a software tool used to establish shot setup requests. The RS inputs this information for each shot and outputs can be work orders configuration parameters sent to ICCS.

2.2 Passive Stakeholders

These passive stakeholders impact the design of the RAS but do not interact with its post commissioning operation, maintenance, or calibration.

2.2.1.1 Target Diagnostics Lead (TDL) – Perry Bell

The Target Diagnostics Lead is responsible for strategic management the Target Diagnostics department. He directs the use of personnel and procurement resources.

2.2.1.2 Shot Analysis and Visualization (SAVi)

SAVi is a software tool that provides post shot data analysis and visualization capabilities. It accesses calibration information stored in Glovia and applies analysis algorithms. It takes input from Locos to understand diagnostic states prior to and during a shot, such as attention value on all transmission paths.

2.2.1.3 Software design, Glovia & Locos – Allan Casey

Signal attenuation is part of the calibration chain, and therefore requires configuration management through Glovia and Locos. The software designer requires SmartLoc location identifiers for any new parts in this chain. He will also need NIF part numbers for each class of part, and unique serial numbers for each piece of hardware.

2.2.1.4 Software designers, CMT – Doug Speck

A new signal attenuation strategy will require updates to pull down menu options within this tool. Behind the scenes calculations may also need updating. The software designer will need to know what are the new attenuation options and what outputs are required to the NIF control system.

2.2.1.5 Software designers, Config Checker – TBD

Config checker is a software tool that access both Locos and CMT, and those does a comparison between diagnostic setup requests (CMT) and actual physical configuration (Locos). Config Checker can be accessed at any time before the shot, and is checked by the lead operator during the shot cycle. This system will need to understand all of the RAS updates to both Locos and CMT.

2.2.1.6 Software designers, ICCS – Jarom Nelson

The software designer will need to understand all possible inputs requests and all control and monitoring specifications of the RAS.

2.2.1.7 Software designers, SAVi – Judy Liebman

The SAVI team is responsible for post shot data analysis and will need to access new attenuation calibration files. This requires knowledge of all new attenuation options.

2.2.1.8 Mechanical designer (MD) – Marty Yeoman

The RAS may need custom fabricated hardware to physically support it. The mechanical designer will need the physical size and shape of any new hardware requiring support. He will need to understand access requirements and how the physical device(s) connect to other hardware in the system.

2.2.1.9 Electrical designer (ED) – Willie Lew

Control of the RAS may require installation of new rack equipment and cabling. The electrical designer will need a list of equipment and locations.

2.2.1.10 Electrical Engineering (EE) – Todd Clancy

The electrical engineer needs all understand all electrical and control requirements for the RAS.

2.2.1.11 Racks and Cables CCB – Sue Poor

This CCB approves any changes to the racks and cabling within the NIF. The CCB expects all electrical and rack dwgs to be completed, reviewed, approved, and released.

2.2.1.12 Authorizing Individual and WAP process (AI) – TBD

The AI governs the Work Authorization Process (WAP) and will need to understand the entire scope of the project, all interfaces, and all stakeholders.

2.2.1.13 *Facility Coordinator – Jim Cox*

All work in the NIF must be scheduled through the Facility Coordinator. He will require the locations, start times, durations, and team makeups.

2.2.1.14 *Operations Manager – Beth Palma*

The Operations Manager will assess and coordinate changes to operations staffing and Qual Cards. She will need to understand and approve the concept of operations. She expects the system to be safe and efficient to operate.

2.2.1.15 *Electrical Authority Having Jurisdiction Inspection (AHJ) – John Hollis*

The AHJ expects all equipment to be safe and safely installed. Powered electrical equipment must be "Listed" or locally inspected and certified safe. He requires access to the electrical equipment list, rack dwgs, electrical dwgs, and to all installed equipment.

2.2.1.16 *Timing and Cross-Timing CCB – Brad Golick*

Any change to the signal path will affect trigger timing and fiducial timing. The timing team will need to know the estimated timing changes, and may need to measure the actual changes once installed.

2.2.1.17 *Integrated Product Review Board (IPRB) – Scott Winters*

IPRB sets the design review standards for NIF. The scope of all design reviews for this project must be approved by this board.

2.2.1.18 *Work Permits*

All work in the Facility requires a permit. Work descriptions and hazards must be identified.

2.2.1.19 *Target Diagnostics CCB – Bob Kauffman*

Any change to the diagnostic that effects or can effect diagnostic quality must be approved by this board. They will need to know scope of change and risks to data quality.

2.2.1.20 *Engineering Design Safety Standards (DSS) Manual*

This manual specifies the requirements with regard to safety installation and operation of engineered equipment.

2.2.1.21 *Engineering Policy Manual*

Establishes applicability for engineering policies and defines authorities for granting exceptions.

2.3 Stakeholder Expectations

The following table lists all stakeholders and their expectations. Each expectation is qualified as a capability of the system, a characteristic, or an expectation. The expectation classification is necessary as they indicate neither a capability nor a characteristic of the system. Generally, these expectations provide guidelines on operation outside the RAS boundaries, define communication guidelines for the RAS design team, or set rules on how to perform work inside or outside the NIF facility.

Table 1: Stakeholder expectations

Stakeholder	Cap, Char, or Exp	Expectation	Rank
NIF Target Diagnostic Coordinator	Cap	The TDC will be made aware of the RAS's shot readiness	3
	Cap	The TDC will be capable of controlling the RAS during the shot cycle	1
Responsible Scientists	Cap	The RAS will allow for a wide adjustment of the sensitivity range of the diagnostic through CMT	5
	Char	The RAS will operate reliably	5
	Char	The RAS will operate consistently	5
	Char	The RAS can be calibrated	5
	Char	The RAS shall be wide band, preferably with no low frequency limit.	5
	Char	The RAS shall not introduce constraints on attenuation value that are more restrictive than the current system	3
Responsible Systems Engineer	Cap	The RAS will allow for adjustment of the sensitivity range of the diagnostic	5
	Char	The RAS will operate reliably in the NIF Target Bay	5
	Char	The RAS shall not introduce signal reflections in the DSR region of the signal trace	3
	Char	The RAS will operate without causing undue risk to the shot quality of the diagnostic	5
	Char	The RAS will not introduce excessive insertion loss	3
	Char	The RAS will indicate when it is not performing within spec	3
National Security Technologies	Char	The RAS will have standard input and output connectors to allow calibration on existing lab equipment	3
Target Diagnostics Lead	Char	The RAS will be cost effective	5
	Char	The RAS can be employed by the maximum number of diagnostic systems on NIF now and in the future	5
Software design - Glovia & Locos	Exp	The RAS SmartLocs, part numbers, and serial numbers will be determined and communicated to the Glovia and Locos software designers	5
	Cap	The RAS configuration will be archived with experimental shot data	4
Software designers - Configuration Management Tool	Exp	All allowable attenuation setup states of the RAS must be communicated to the CMT software designers.	5

	Exp	The method for CMT setup requests of the RAS must be determined, will there be calculations?	5
Software designers - Information Command and Control Systems	Exp	RAS input and output control/monitoring signal formats must be determined	5
Software designers - Shot Analysis and Visualization	Exp	All allowable CMT attenuation setup states of the RAS must be communicated to the SAVi software designers.	3
Mechanical designer	Char	The physical size, mass, and connection strategy of the RAS hardware must be compatible with existing hardware	3
Electrical designer	Exp	All changes to existing electrical dwgs caused by the RAS must be communicated to the ED	4
Electrical Engineering	Exp	National, state, and Lab electrical codes must be followed in the design, installation, and operations of the RAS.	4
Racks and Cables CCB	Exp	All rack modifications caused by the RAS must be documented	4
Authorizing Individual and WAP process	Exp	The RAS team will complete a thorough WAP	4
Facility Coordinator	Exp	All RAS work in the facility must be coordinated with the FC	4
Operations Manager	Exp	The specific reductions in diagnostic setup support caused by RAS automation must be communicated to the OM for updates to staff and procedures	3
Electrical Authority Having Jurisdiction Inspection	Exp	All RAS equipment will be "Listed" or inspected and certified.	5
Timing and Cross-Timing CCB	Exp	Estimates of the changes to signal path timing caused by the RAS will be communicated to the NIF Timing team. Bench or in-situ measurements may need to be performed.	3
Integrated Product Review Board	Exp	The RAS will performed all design reviews in accordance with IPRB standards and approval	4
Work Permits	Exp	The RAS installation and commissioning team will obtain released work permits for facility work	4
Target Diagnostics CCB	Exp	All benefits and risk factors to data quality that the RAS introduces will be accessed and communicated to the Target Diagnostics CCB	4
Engineering Design Safety Standards (DSS) Manual	Exp	The RAS will follow all Lab Engineering Design Safety Standards	5
Engineering Policy Manual	Exp	The RAS will follow all LAB Engineering Policies	4

2.4 Key Stakeholders and Expectations

The following stakeholders and expectations are key to the success of the RAS.

- Responsible Scientists
  - The RAS will allow for a wide adjustment of the sensitivity range of the diagnostic through CMT
  - The RAS will operate reliably and consistently
  - The RAS can be calibrated
  - The RAS shall be wide band, preferably with no low frequency limit.
- Responsible Systems Engineers
  - The RAS will operate without causing undue risk to the shot quality of the diagnostic
- Target Diagnostics Lead
  - The RAS will be cost effective
  - The RAS can be employed by the maximum number of diagnostic systems on NIF now and in the future

The RS, RSE, and TDL have the largest stake in the success of the RAS. The TDL determines organizational strategy and resource usage, and has initiated this project with the intent to reduce operational costs within the NIF facility. The RS and RSE are both responsible for the resulting diagnostic data and drive the quality requirements for the system.

2.5 RAS Design Team

The following stakeholders are considered part of the design team and may present at any design review activities: The Responsible Scientist, the Responsible System Engineer, all software designers, the Mechanical Designer, the Electrical Designer, the Electrical Engineer, and the Timing Team.

3. SYSTEM OPERATIONAL CONTEXT AND REFERENCE OPERATIONAL ARCHITECTURE

3.1 System Operational Context

3.1.1 The Current Attenuator System

The current coaxial attenuation system requires hands on manual manipulation of the hardware to implement shot setup activities (see Figure 1). Target Diagnostic Operators retrieve shot setup requests for each diagnostic through CMT and diagnostic states through Locos. Requests are compared to actuals to identify required changes. Once identified, the needed attenuator hardware and tools are gathered for the job. Applicable work permits are found and printed, as well as any needed procedures. The team then moves to the local job site where a SPA is performed and the physical work commences. The team moves to each necessary job site until all attenuators are properly changed. Once the physical work is completed, the current state of the diagnostic is manually updated in Locos. The process then repeats for the next diagnostic.

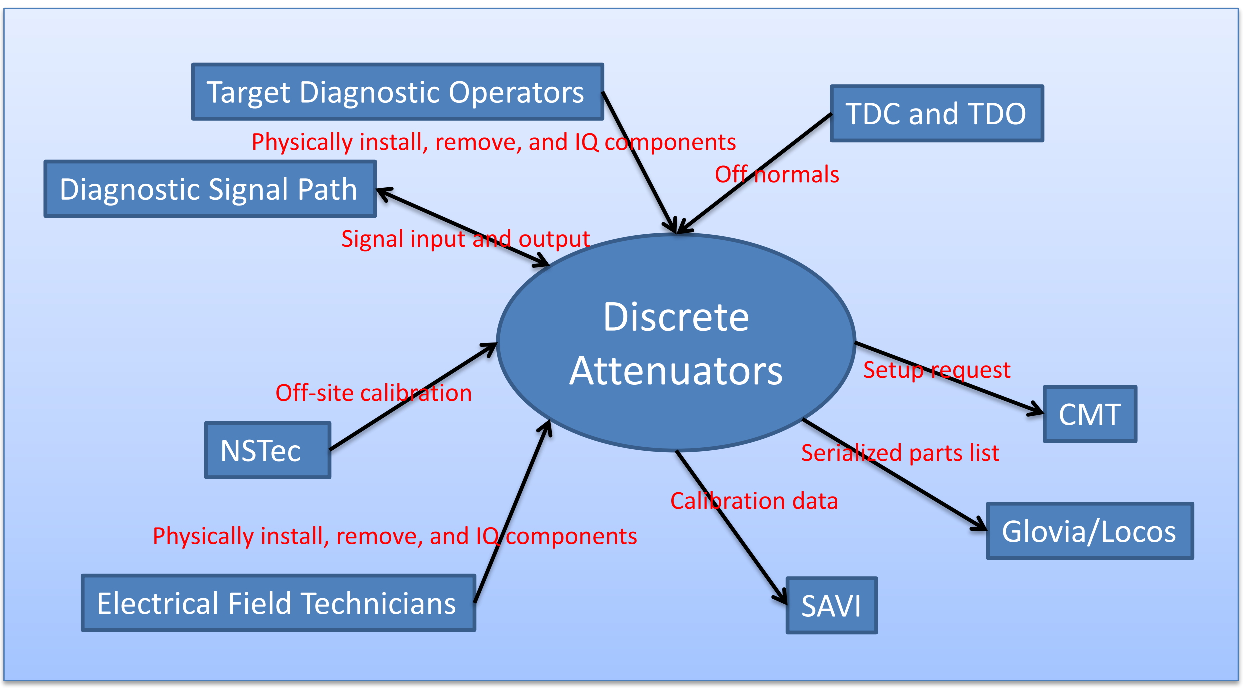

Figure 1: Current operational context.

The photo below depicts a number of fixed attenuators that are used in NIF Target Diagnostics. Shown are two N connector attenuators and a single, smaller, SMA connector type.

Figure2: Typical fixed attenuators

The following two photos show how these fixed attenuators are used in the field. They are typically inserted in-line with the signal path, and thus have a male connector type on one side and a female on the other.

Figure3: Signal path Example

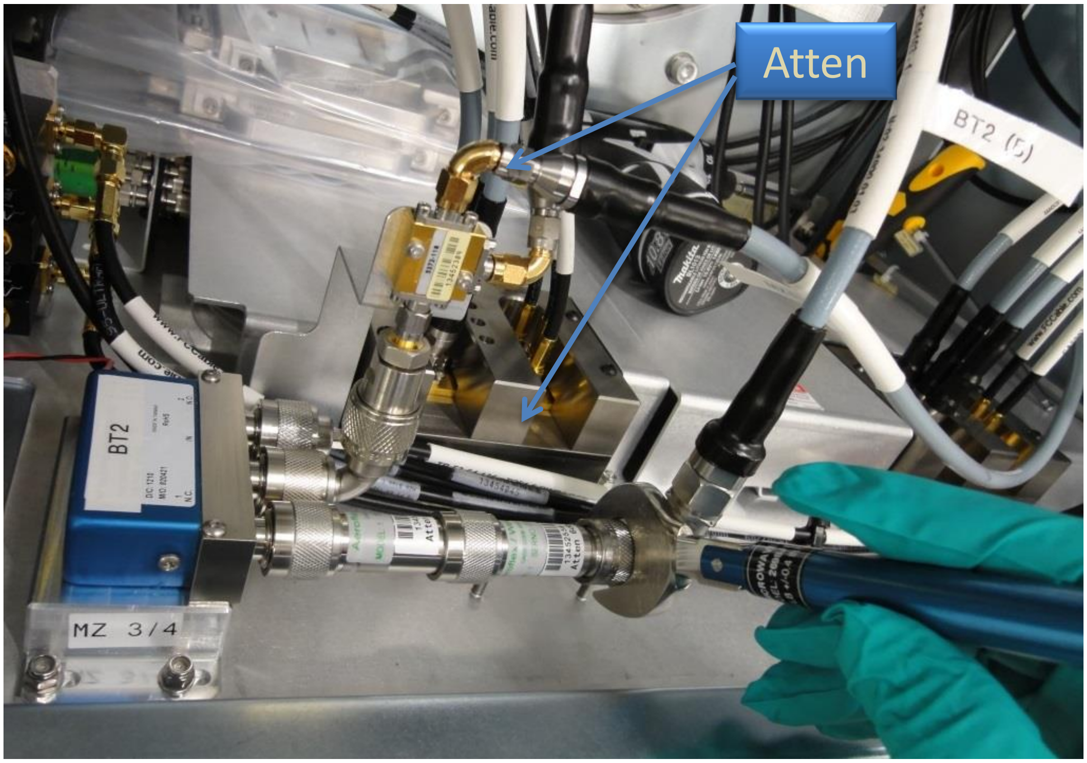

Figure4: Signal path Example

3.1.2 The RAS

The purpose of the RAS is to eliminate the need for human intervention in the setup process of the coaxial attenuators (Figure below). Although there are possible system architectures that may not fit the operational context described below, it is unlikely that these non-conformal architectures will be selected. For more information see Section 6.

The RAS is inserted in the diagnostic signal path and during a NIF system shot, accepts a time varying electrical input pulse. The RAS outputs an attenuated signal that continues down the signal path and is eventually recorded on a digitizing oscilloscope. Prior to a system shot, the RAS must be remotely configured by the NIF control system (ICCS) to the requested parameters from the Configuration Management Tool. The RAS must also communicate its current configuration to the CMT, thus verifying the condition of the system prior to and during a shot. All RAS hardware will be serialized and system architecture will be archived for each shot based on the Locos database. Periodic maintenance is required, not more than once per year, for calibration. If the reference model is followed, the hardware will be removed by electrical field technicians and calibrated by NSTec off-site. This team should consider the future implementation of in-situ automatic calibration. The hardware is then re-installed and new calibration files are formatted and uploaded to the SAVI system for use in post shot data analysis.

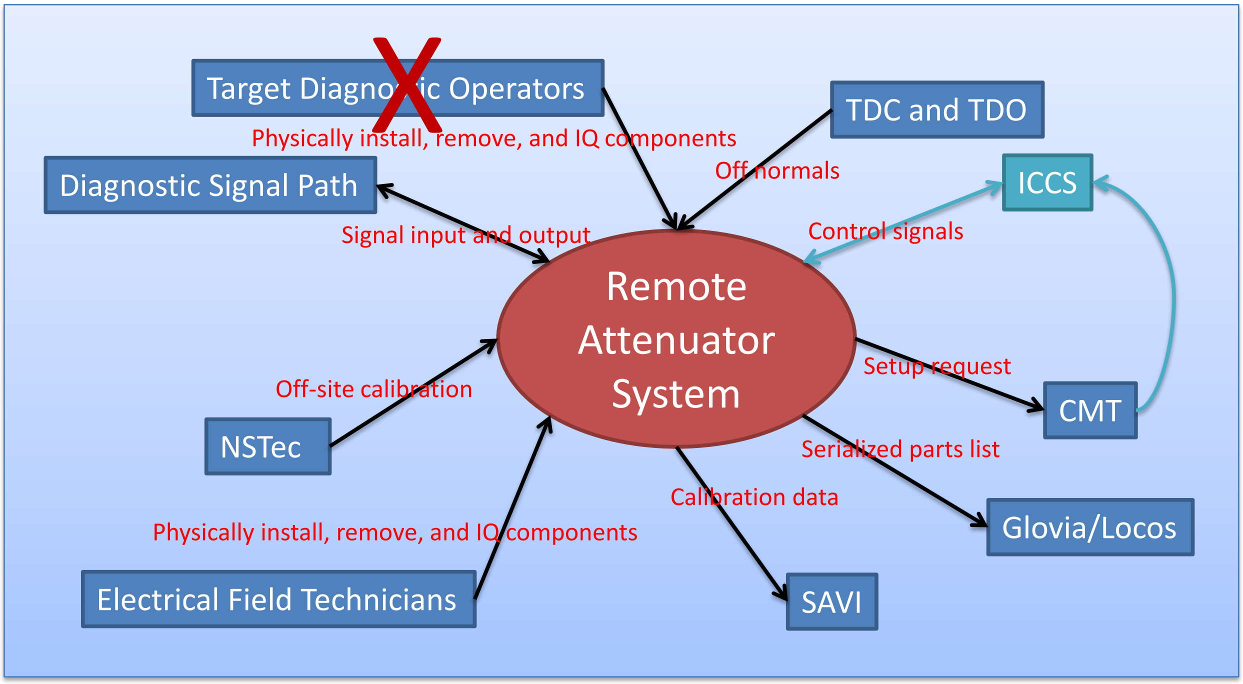

Figure 5: The RAS operational context.

The RAS will consist of hardware with control and communication software inputs and outputs. Also the RAS will be part of a larger diagnostic system under the control of the RS and RSE, who perform diagnostic setup requests through CMT, upload calibration files, and schedule calibration and maintenance activities. In this context, the RS and RSE are part of the RAS, and act as the interface boundary to these other systems mentioned.

The RAS design team consists of mechanical and electrical designers that are led by the RS and RSE. The system boundary also includes technician support for installation of the system into the diagnostic at NIF. Note that there are no software designers on the team. Therefore software to support the RAS will either need to be purchased off-the-shelf or contracted outside of NIF or within a NIF subsystem.

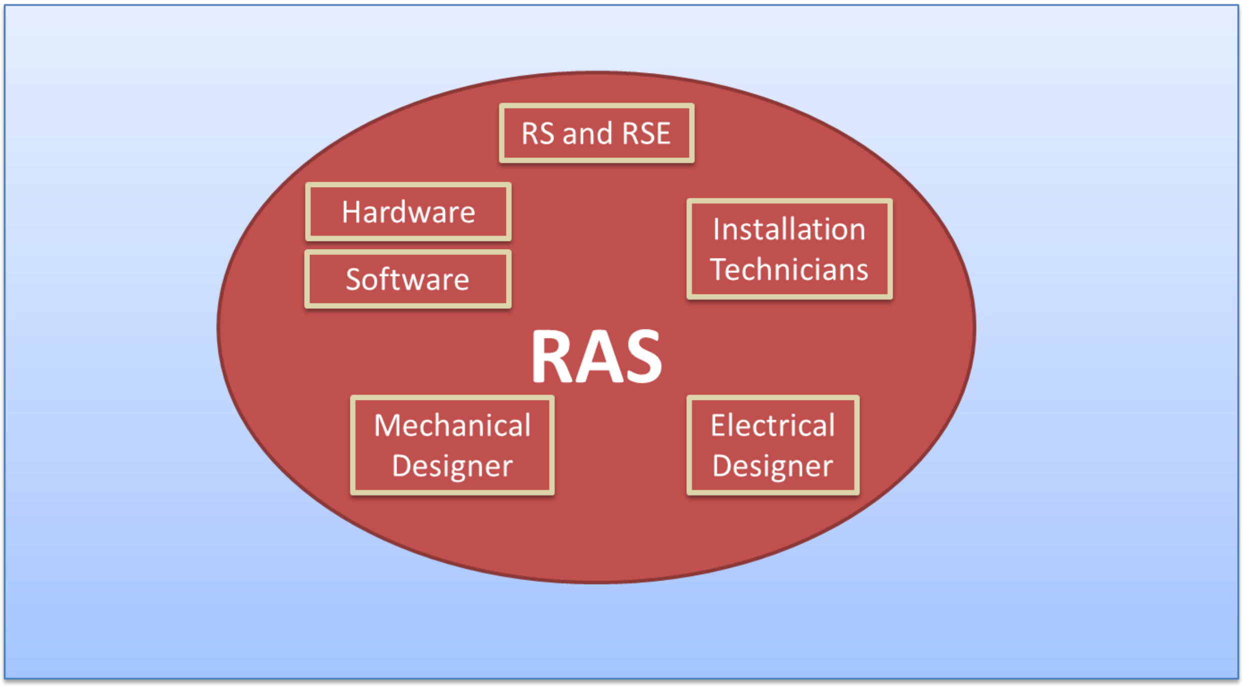

Figure 6: The Remote Attenuator System boundary

4. SYSTEM DRIVERS AND CONSTRAINTS

The primary design objective for the RAS is to reduce the lifetime operational costs for running diagnostics at NIF. Total project cost must be compared to current and future operating cost so that a cost-benefit analysis can be used to justify the expenditure. There is no hard deadline or schedule, but it would be expected that initial fielding occur in FY15. More concrete drivers and constraints are listed in the table below.

Table 2: Major RAS Performance Requirements

Performance Parameter	Capability or Characteristic	Requirement
Cost	Char	The RAS will be cost effective.
Reliability	Cap	The RAS will operate reliably in the Target Bay and Mezzanines
Voltage Survivability	Cap	The RAS must withstand 1000 test pulses with a voltage peak of X and a full-width-half max of 10 ns, with no measurable change in performance.
Repeatability	Cap	Each attenuation value of the RAS must be repeatable to within X after 1000 switching cycles.
Noise Output	Cap	The RAS must not introduce any measurable noise into the diagnostic signal path as measured by the highest sensitive channel of the recording oscilloscope.

5. OPERATIONAL SCENARIOS

There are two major use cases for the RAS. In the first, the Responsible Scientist as the initiating user and the purpose is to configure the RAS for an experimental shot at the NIF. In the second, the TDO or TDC must verify, during the shot cycle, that the RAS is setup properly for the shot.

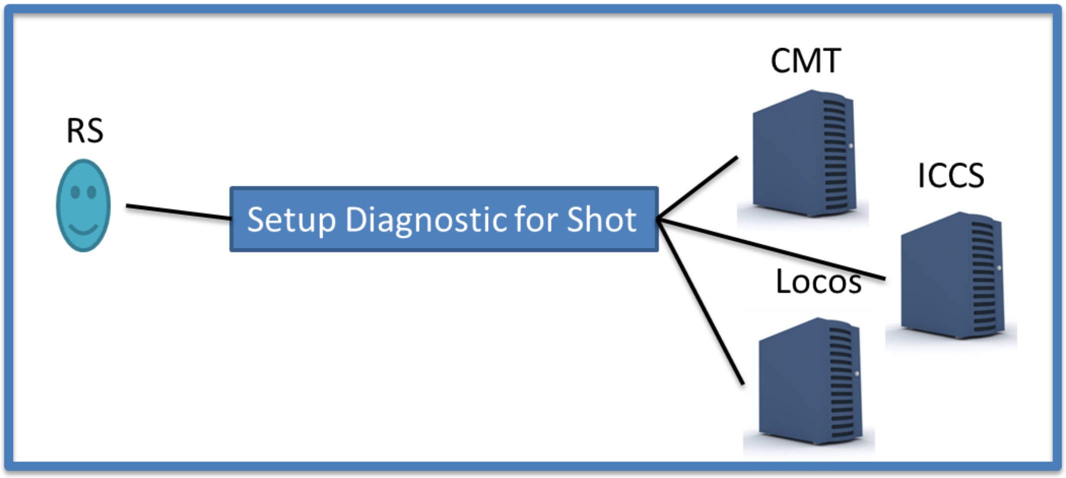

Figure 7: Diagnostic setup use case

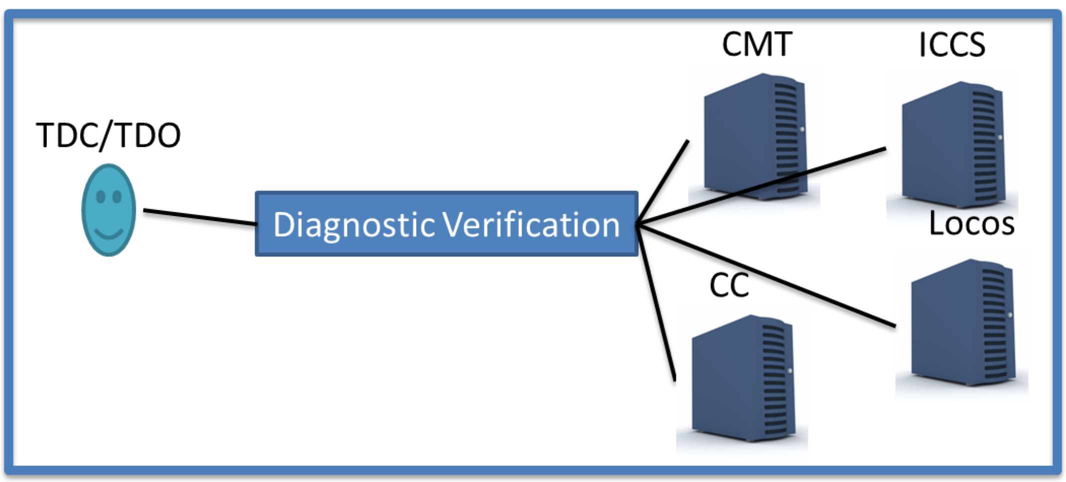

Figure 8: Diagnostic verification use case

5.1 Diagnostic Setup

In this use-case, the RAS, including diagnostic RS, and its inputs and outputs are shown in red. All descriptions of activities outside this boundary are qualitative as they are not the responsibility of the RAS design team. It is however helpful to have a general sense of the sequence of events.

To start, the RS accesses the software tool CMT via a personal computer. The RS may adjust all diagnostic parameters manually, or load a pre-configured template. In each case, a value is stored for each requested attenuation on each channel of the diagnostic. At some point during the shot cycle, ICCS will query CMT for a subset of the diagnostic setup parameters. Only the parameters for which ICCS can control are requested. CMT will send the parameters to ICCS.

ICCS communicates directly with the RAS and will initiate a query of the current state. The RAS will respond with the current state. ICCS will determine if a change is needed and if so, send a new state command to the RAS. ICCS will then repeat the state query and the RAS will respond in turn. Once the state of the RAS corresponds to the state requested, ICCS will send the current state to Locos. The RS can then verify shot readiness through Locos at any time.

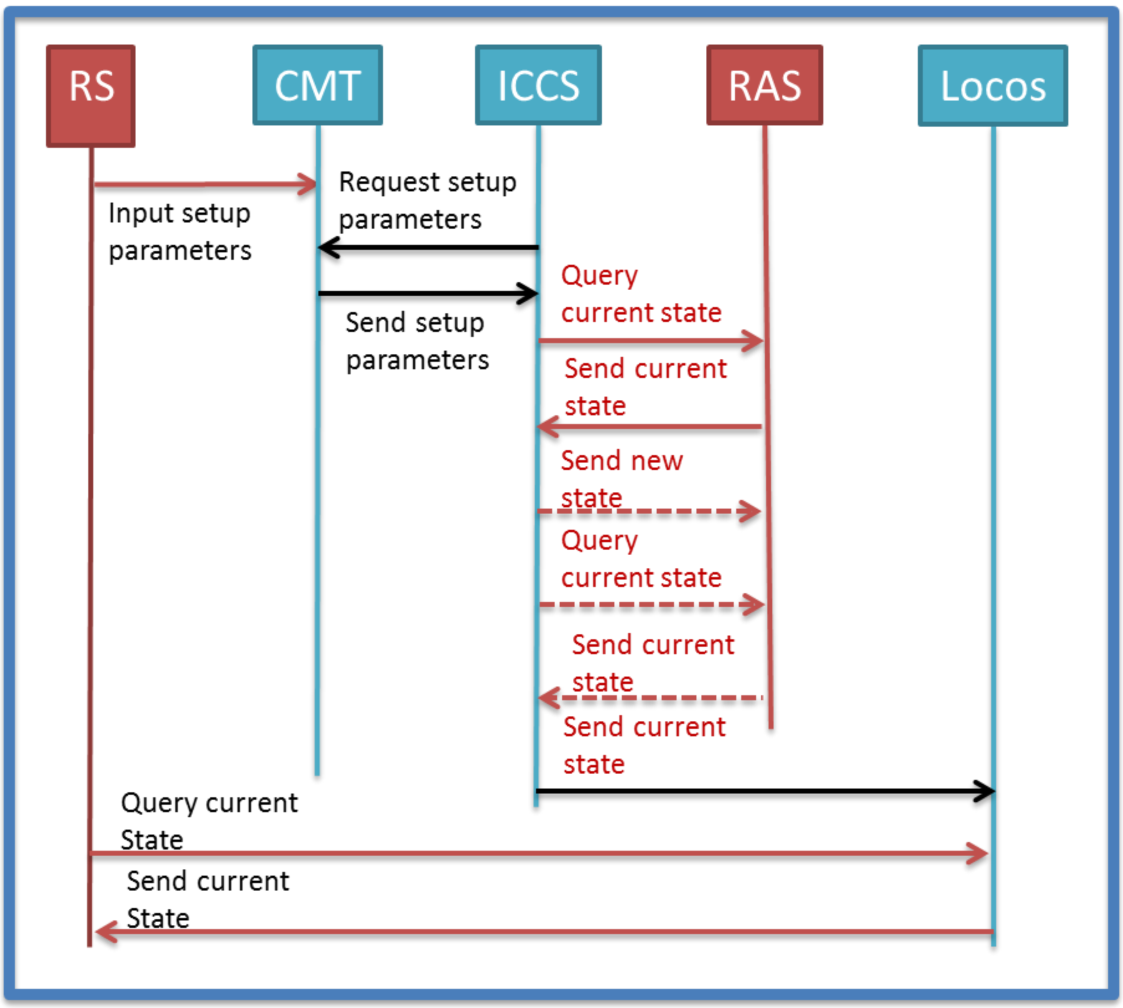

Figure 9: Diagnostic setup use case detail

5.2 Diagnostic verification use case

In this use-case, the RAS boundary is indicated in red. As you can see from the figure below, most of the verification process occurs outside our boundary; however we feel it is helpful to illustrate it.

In this use-case, the TDO or TDC will request a ConfigChecker (CC) report which indicates the status of all shot setup hardware requests, either green for installed, or red for not installed. ICCS receives the request and passes it on to CC. CC then requests the current state of the diagnostic from Locos, which maintains a real time database of system configurations. Locos is updated at the time of hardware installation by ICCS, which in turn received this information form the RAS. Note that ICCS doesn't have to make a request to the RAS for this information; it is automatically uploaded as part of the setup procedure.

CC also requests the setup configuration desired from CMT. CMT responds with the requested configuration and Locos responds with the current configuration. CC then makes a comparison of requested to actual and then sends the green and red status indicators through ICCS to the TDO or TDC.

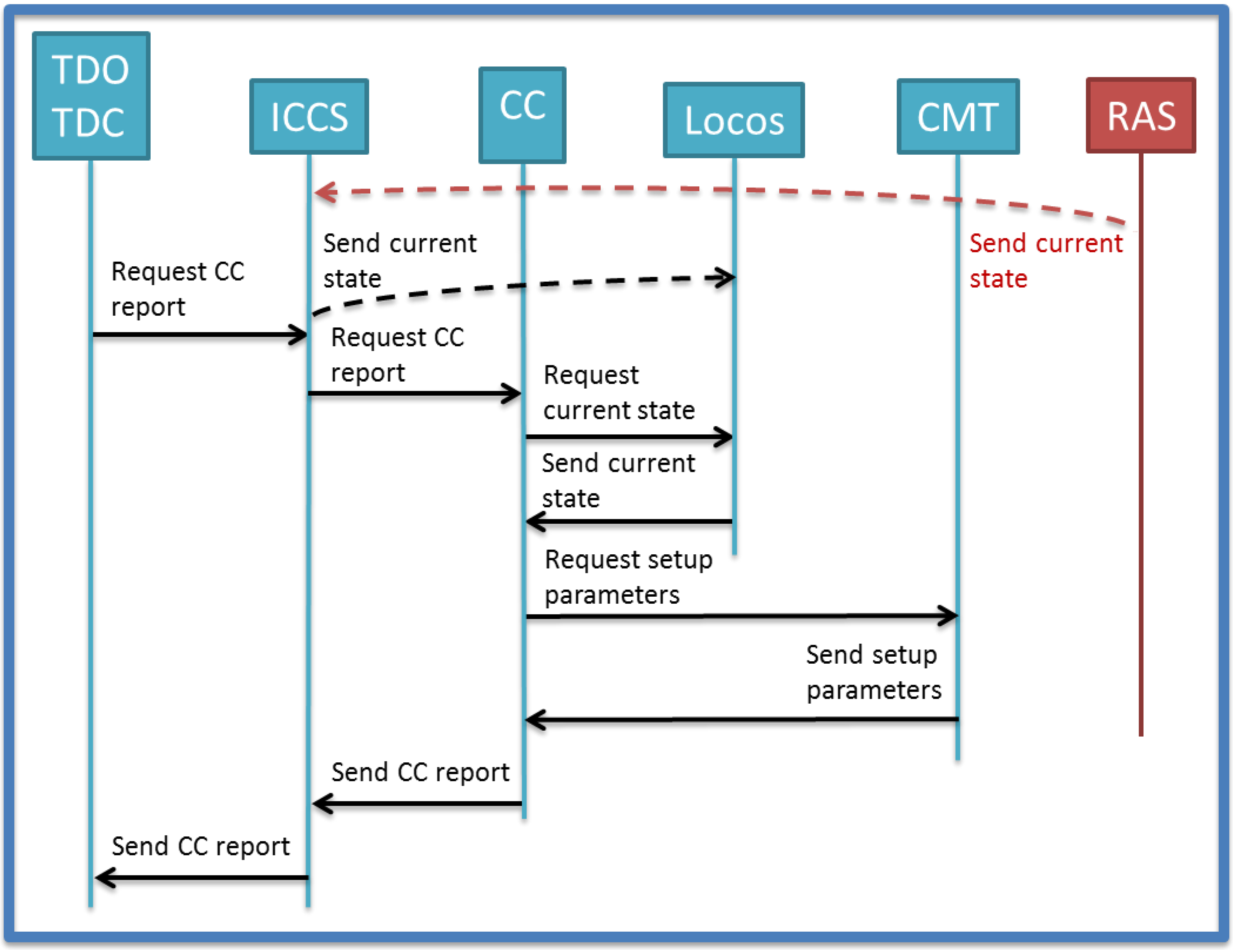

Figure 10: Diagnostic verification use case detail

6. IMPLEMENTATION CONCEPTS AND RATIONALE

In this section we will support the system selection rationale with a Quality Function Deployment (QFD) matrix and an architectural trade study. The QFD matrix is used to relate the characteristic expectations into system objectives or non-functional requirements. The trade study is then used to down select from a handful of proposed system architectures to the proposed system.

6.1 Quality Function Deployment

In the blue column of the matrix below lists all of the characteristic expectations as listed in Section 2. These are the *whats* of the RAS, and the *hows* are listed in the top row in red. The *hows* are the system objectives or non-functional requirements. We recognize that the *hows* of this matrix may be further refined into more concrete and detailed *hows*, we intend to do so, and this matrix is the first order of this process.

Each *what* is ranked in priority from least (1) to most (5) and a correlation score is computed at each interaction between the expectation and requirement? Looking across a row or down a column, we note that there is a strong correlation between a great number of expectations and requirements and perhaps this indicates a low degree of precision, and a further refining is in order.

Table 2: QFD Matrix for the RAS

Characteristic Expectations and Priority		The RAS will have a state life cycle of 10 years	RAS attenuation states will not alter with time	The RAS will have a 3db bandwidth from dc to 5 Ghz.	The RAS shall have an attenuation dynamic range of 50db	The RAS will not employ solid state circuitry in the TB	RAS may employ delay lines for DSR reflection mitigation	The RAS shall have a minimum insertion loss of 1db	The RAS will self monitor for faults	The life cycle cost of the RAS shall be <$100k per Diag	The RAS will be small in size and weight.	Support of the RAS will not harm cables, connectors, etc.	The RAS will operate without human intervention	Expected RF inputs will not alter the RAS atten states	The RAS will vary atten with no larger than 3 db steps	The RAS will be controlled electronically	The RAS will employ standard RF connectors
The RAS will operate reliably	5	2				4			2	4		3	4	5		4	2
The RAS will operate consistently	5	1	5			2			1	3		3	4	5		4	
The RAS can be calibrated	5		5		1					2		3	5				4
The RAS shall be wide band, preferably with no low frequency limit.	4		2	5			4	2						2			3
The RAS shall not introduce constraints on attenuation value that are more restrictive than the current system	2				5			4						1	5	2	
The RAS will operate reliably in the NIF Target Bay	5	2	3			5			2	4		3	4	5		4	
The RAS shall not introduce signal reflections in the DSR region of the signal trace	1		2	2	1	1	5		2			3	2				5
The RAS will operate without causing undue risk to the shot quality of the diagnostic	4	3	4			2	3	4	2			5	3	5		3	
The RAS will not introduce excessive insertion loss	2					3		5									5
The RAS will indicate when it is not performing within spec	1		3						5				3			5	
The RAS will have standard input and output connectors to allow calibration on existing lab equipment	2	5	4	4				4		3							5
The RAS will be cost effective	5	4	4	1	2				3	5	1	3	5	4		5	
The physical size, mass, and connection strategy of the RAS hardware must be compatible with existing hardware	4						3		2	4	5	5					3

6.2 System Evaluation and Selection

These are the system architectures to be evaluated:

- Control gain through detector bias voltage
- Permanent attenuation below maximum measureable levels
- Mach Zehnder wrapping
- Optical filtering
- Neutron and gamma filtering
- Manual switches
- Electrically controlled discrete attenuators

6.2.1 Control gain through detector bias voltage

Most of the scope-based diagnostics on NIF require some degree of high voltage bias to adequately detect the experimental signal of interest. This is necessitated by the large amounts of gain required in order to adequately measure and record the signal. Common detector types that employ high voltage bias include PMT, PD, XRD, and CVDD. From the table below, you can see the distribution of these detectors for each diagnostics listed. The table includes both existing and planned diagnostic systems.

Table 4: Scope based target diagnostics on NIF

Diagnostic	Detector
EMP 102,84	Antenna
Neutron Test Bench (NTB)	All
Neutron Test Well (NTW)	All
NTOF 18M-SPEC 161,56 (SP)	PMT,PD
NTOF 20M-SPEC 116,316 (A)	PMT,PD
NTOF 20M-SPEC 90,174 (E)	PMT,PD
NTOF 4M-DTHi 064,330	PMT,PD
NTOF 4M-DTLo 064,330	PMT,PD
NTOF 4.5 M-BT 064,136	CVDD
NTOF 20M-IgnHi 116,316	CVDD
DANTE 064,350 (2)	XRD
DANTE 143,274 (1)	XRD
Fflex 90, 110	XRD
GRH-6M 64, 20	PMT
Super Gas Cherenkov Detector	PMT
Low Energy Neutron Spec (LENS)	PMT
Curved Crystal Gamma Spectr	PMT
GEMS	PMT
Furlong	PMT

PCD 90,315	CVDD
PCD 0,0	CVDD
PCD 90,78	CVDD
PCD 90,78	CVDD
SPBT 161,146	CVDD

Since output gain is function of both the input signal flux and the bias level, we can increase dynamic range by control of the bias. The most significant drawback to this approach is that it can dramatically complicate calibration. A lot of diagnostics, nTOF for example, operate at one or two bias levels for the sole purpose of simplifying calibration. Adding additional fixed bias levels or worse, employing a continuously variable bias, would induce more calibration uncertainty and require more NIF shots for calibration, which as we've explained are expensive.

Another drawback is that some systems have a limited bias range for which the detector is linear or useful. At the same time, this approach has been successful for some diagnostics such as GRH.

6.2.2 Permanent attenuation below maximum measureable levels

If we could determine what the maximum expected output level of the detection subsystem might be, then we could introduce a single fixed attenuation that is never re-configured. Since this reduces the overall sensitivity of the diagnostic, it could only be employed by very high dynamic range systems, or systems for which the measurement range is permissibly small. Although effective in these cases, it does not meet the mission objective of improving the dynamic range of the diagnostic system.

6.2.3 Mach Zehnder wrapping

A Mach Zehnder transmission system is a complex method for converting RF electrical signals to optical, and then back to electrical before input into a digitizing oscilloscope. Typically the purpose of this system is to 1) increase the bandwidth of the transmission system, or 2) provide over voltage protection of sensitive digitizers.

There is another benefit to the MZ system which is increased dynamic range. This is the result of the linear electrical signal be transformed into a sinusoidal output that never exceeds the pi/2 limit of the MZ. Un-wrapping the MZ signal reproduces the linear output without the need for overlapped channels, or other methods of dynamic range extension. As long as the input voltage to the MZ does not exceed damage levels, and the bandwidth the scope can accommodate the wraps, no additional attenuation is necessary.

MZs have not been employed solely for this dynamic range benefit for a number of reasons. First, the MZ is complex, difficult to calibrate, and adds reliability risks. Also, MZ systems are very expensive, costing upwards of $200k per detector channel to implement.

6.2.4 Optical filtering

Optical filtering works in the same manner as electrical attenuation, only it operates on the optical signal before it is converted to electrical. Clearly this would only work on the two-stage detectors employing PMTs and PDs, as these have an optical path between the initiator and the electrical transducer. Optical filters are often in use currently and they require the same or more human intervention to setup as the reference system of fixed attenuators. Automatic remote filter installation is project that is currently underway in a parallel effort to reduce operational costs.

6.2.5 Neutron and gamma filtering

High-Z material may be used to shield neutrons and gammas from reaching the detection device. This approach is already employed for many systems with respect to background level shielding. It is also employed minimally for the direct sources; however, increasing this shielding would lead to higher background levels. Also, the large physical size and weight required would be difficult if not impossible to implement cheaply or remotely.

6.2.6 Manual switches

Using inline attenuation devices with manual switches would improve on the current system, reducing shot-to-shot setup time, improving reliability, reducing maintenance costs, and adding flexibility. This is however a half-measure, as human intervention is still required for configuration changes and the total cost savings would be significantly reduced. Pasternak, Fairview Microwave, Narda, Aeroflex all make manually operated variable attenuators.

Figure 11: Manually operated variable attenuators

6.2.6.1 Electrically controlled discrete attenuators

Electrically controlled discrete attenuators have many advantages. Once setup, they require minimal human intervention for shot-to-shot operations. The RS is still required to select the proper attenuation level through CMT, but that is the extent of labor necessary and the rest of the functionality of the system is fully automated. Periodic maintenance may still be required for calibration, but this is an annual operation at most, and there are methods for in-situ calibration that can be explored.

6.2.7 Trade Study Parameters

In order to determine the best approach to the RAS, team brainstorming has resulted in a number of plausible operational concepts for the control of signal levels on the scope-based NIF diagnostics. Note, that not all of these approaches fit the reference model of device insertion on the coaxial transmission line.

6.2.7.1 Wide adjustment range

Scope based diagnostic systems at NIF can be characterized by three subsystems, a detection or signal generation start, a transmission middle and a recording end. Signal generation is introduced by a neutron, gamma-ray, X-ray, or optical initiator. Being a scope based system; the initial signal is converted to an electrical signal at some point, typically on the detection side, but not always. The dynamic range of the detection hardware may be fixed or may also be variable via hardware changes or voltage bias changes. Hardware changes are operationally costly.

The purpose of the RAS is to increase dynamic range of the diagnostic system. This is important due to the fact that the NIF produces these signal initiators at levels spanning many orders of magnitude. For scope based systems, there is a minimum and maximum signal level that can be recorded without clipping or cause damage to electrical parts in the system. A typical channel on a high bandwidth digitizer may have 35 db of dynamic range. Channel overlapping can be employed, typically with 4 or less channels, yielding roughly 120 db, or six orders of magnitude. Use of attenuation can extend this dynamic range.

Most systems have hardware limits on the their signal output, therefore employing attenuation is in turn limited by the maximum output of the detector and the minimum detectable signal by the recording subsystem. Some diagnostics can benefit from 20 db of additional dynamic range, and others can use as much as 80 or more. The RAS will be more effective with the widest possible range, within a limit of about 100db or so.

6.2.7.2 Operate reliably

Operational reliability is very important to the diagnostic RS's, and the NIF community as a whole. Each NIF shot can be estimated to cost a million dollars or more and successful data collection makes the best use of these this resource. Some degree of risk is always involved in complex systems, and our goal is to minimize this and produce the most reliable system within our budget constraints.

6.2.7.3 Operate consistently

Subtly different from reliability, operational consistency implies a characteristic of stability with time and when subjected to operational use. A RAS that is not highly stable would require higher levels of monitoring and more complex calibration strategies. More routine maintenance planning may also be required, which is costly and undesirable.

6.2.7.4 Can be calibrated

The requirement for calibration is key to a successful diagnostic. A system can be calibrated under our current methods if it has standard input and output connections, and is stable. Reliability, consistency, and calibratable are so closely related, that we could have listed them as a single key expectation.

6.2.7.5 Wide band

The diagnostic systems on NIF vary greatly. Most of the systems can be characterized with a near DC low frequency limit. In reality, the cutoff is approximately 2.5 Mhz for most systems, but some could be as low as 250 khz. The upper frequency limits range from a few hundred Mhz to up to 12 Ghz. Most systems have upper frequency limits of about 2-6 Ghz.

6.2.7.6 Reliable in the Target Bay

Due to the proximity of the TB to the target and the lack of shielding in this area, there is a high EMP, X-ray, gamma-ray, and neutron environment. X-ray's and gamma-rays are generally not much of a concern for RF active and passive componentry.

EMP mitigation is typically straightforward and is implementing at the diagnostic system level. The RAS must be integrated harmoniously with this system EMP mitigation approach.

Neutron mitigation can be more problematic. Neutron flux is high in the TB, and is incident from all angles. Solid state circuitry upset and damage levels are routinely exceeded on NIF ignition shots. Other things to consider with regard to neutron mitigation:

- Very few diagnostics require the RAS to be in TB (only nTOF4.5 BT comes to mind)
- The legacy attenuation system for most diagnostics exists in the Mezzanines and is well shielded from neutron radiation.
- Employing a different RAS architecture inside the TB then outside may be warranted

6.2.7.7 Cost effective

The primary purpose of this project is to reduce lifetime operational costs of scope-based diagnostic systems at NIF. The largest driver of operational costs within the NIF facility, other than replacement of optics, is labor. Mission success therefore is highly dependent on the reduction of human intervention in the signal level control and recording of diagnostic shot data. Other contributors would include frequent hardware re-configurations, or calibrations service, both of which are also highly correlated with labor costs. Systems that are unreliable or require large startup costs are less desirable.

6.2.7.8 Maximum # of systems

Being applicable to the maximum number of systems on NIF can be tradeoff between mission effectiveness, cost, and performance. Given the diversity of systems on NIF, one should not assume that maximum usefulness will reduce costs. Care should be taken in the design to accommodate multiple system needs and to not sacrifice performance and versatility.

6.2.8 Trade Study

The system concepts were evaluated for their ability to meet the weighted system objectives, and scored suitably. Both the weighting and scores were on a scale from 1 (least) to 5 (most). Each objective score was multiplied by the corresponding objective weight and then summed to a total.

Table 3: System trade study matrix

	Wide adjustment range	Operate reliably	Operate consistently	Can be calibrated	Wide band	Reliable in the Target Bay	Cost effective	Maximum # of systems	Total
Weight	4	3	3	5	2	1	5	4	**27**
Detector bias voltage	2	2	2	1	5	5	2	2	**50**
Permanent attenuation below maximum measureable levels	1	3	5	5	5	5	5	2	**93**
Mach Zehnder wrapping	5	3	3	3	5	5	2	4	**78**
Optical filtering	2	4	4	4	4	5	1	1	**70**
Neutron and gamma filtering	1	5	5	4	5	5	1	1	**74**
Manual switches	5	3	3	5	4	5	1	4	**81**
Electrically controlled discrete attenuators	5	5	5	5	5	3	5	4	**113**

7. PROPOSED SYSTEM ARCHITECTURE

7.1 Recommended Configuration

The results of the trade study suggest that the best approach would be to use electrically controlled discrete attenuators. In this form, the RAS would employ four major subsystems, an RF input and output interface, an attenuator subsystem, local actuation, and a control interface.

Table 5: RAS Subsystems

Subsystem	Recommended Configuration	Notes
RF Interface	Coaxial. SMA and N-type connectors are the most widely used at NIF.	SMA is compatible with 3.5, and 2.9.
Attenuators	Discrete passive lumped elements.	Passive lumped elements are stable.
Local Actuation	Inside TB: Relay switches Outside TB: Solid state switches	Solid state circuitry is incompatible with NIF Target Bay operations due to high neutron flux.
Control interface	Inside TB: Relay pins Outside TB: Digital logic, or TTL	Digital logic implies the use of on-board solid state circuitry.

Some off-the-shelf solution may incorporate most of these subsystems in a single integrated unit. Possible RAS systems fall into two main categories, those with solid state control and switching integrated into the remote device, and those that employ relay switching and no control. For the latter, the control circuitry can be non-local to the remote device and tied together by relay control voltages. Solid state circuitry is problematic in the Target Bay as they are susceptible to upset and damage when exposed to the high neutron flux of a NIF experiment.

7.2 System Requirements and Goals

This section lists the system requirement that have been formulated from the use-cases and QFD matrix. Whereas the previous lists of expectations, *whats*, *hows*, etc, may have been broadly defined and vague, the system requirements outlined here are concrete and specific. Also listed here are the system goals, which are desirable to achieve in the final system, they are however secondary *nice-to-haves*. Each requirement and goal has been designated with a verification test method corresponding to one of Inspection (I), Measure (M), Demonstrate (D), or Analysis (A).

Regarding requirements for input and output communication, you'll notice that we haven't defined any. The ICCS system at NIF is capable of interfacing with any and all conceivable communication standards. It is the responsibility of the RAS design team so select a standard that meets system goals and then properly communicate this structure to the ICCS team.

Table 7: System Requirements

Requirement	Goal	Test
All RAS equipment shall pass AHJ inspection for safety.		I
The RAS shall be capable of a minimum of 30,000 switching cycles before failure		M
The RAS shall have a mean time between failure of 50 years		A
The RAS attenuation states shall not drift more than +/- 2% over two years of use.		M
	The RAS should be able to detect and report a change to its time delay calibration of more than 5 ps.	D
	The RAS should be able to detect and report a change to its attenuation calibration of more than 2%.	D
The life cycle cost of the RAS shall be < $100k per Diag		D
Standard shot setup and operation of the RAS shall be through electronic computer control only.		D
The RAS shall have a 3db high frequency cutoff of 5 Ghz or more.	The RAS should have a high frequency cutoff of 18 Ghz.	M
The RAS shall have a 3db low frequency cutoff of 200 khz.	The RAS should have a low frequency cutoff of DC.	M
The RAS shall have a minimum insertion loss of 8 db or less at 5 Ghz.	The RAS should have a minimum insertion loss of 1 db or less at 5 Ghz.	M

The RAS shall have a band pass flatness of +/-3 db	The RAS should have a band pass flatness of +/1 db	M
The RAS shall have a maximum power rating of at least 1/4 watt	The RAS should have a maximum power rating of at least 5 watt	M
The RAS shall be capable of withstanding 10 NIF shots producing a neutron flux of 10^17 n without measurable damage.	The RAS shall be capable of withstanding 10 NIF shots producing a neutron flux of 10^19 n without measurable damage.	D
The RAS shall use input and output RF connectors that are compatible with SMA	The RAS should use input and output RF connectors that are compatible with N-type	I
The RAS shall be insertable such that it employs a female connector on one side and a male connector on the other.		I
The RAS shall be capable of varying attenuation in steps of 3 db or less	The RAS should be capable of varying attenuation in steps of 2 db or less	M
The RAS shall be capable of reaching a maximum attenuation of 50 db.	The RAS should be capable of reaching a maximum attenuation of 80 db.	M
	The RAS should be supplied by a USA retailer	I

7.3 Comparison of off-the-shelf solutions

A market survey was performed in an attempt to identify all manufacturers of remotely variable attenuators that meet our system objectives. We recognize that off-the-shelf solutions are likely to be less costly to implement and maintain over the life cycle of NIF. Once a list was compiled, the component specifications where compared qualitatively to a subset of system requirements as a starting point for conceptual design. See the table below.

Other well-known manufactures that do not manufacture stepped attenuators, neither manually operated or remote, and are not reviewed here are Barth, Picosecond Pulse Labs, Anritsu, and Maury Microwave.

Table 7: Off-the-shelf hardware comparison

		High bandwidth	Low cutoff (DC?)	Low insertion loss	Flat atten response	V damage threshold	Radiation resistant	Ease of installation	N & SMA Compatible	Size and weight	Useful range	Cost	USA manufacturer	Integrated solution	Total	Total (-Rad)
	Weight	5	5	4	2	5	15	2	3	2	3	1	2	2	51	36
GigaBaudics	PA13	5	5	1	2	1	1	4	2	4	4	3	5	4	129	108
Mini-Curcuits	ZX73	1	3	2	1	2	1	3	2	5	2	5	4	3	100	79
Agilent	8494, 5, 6 G	2	5	4	4	4	1	5	5	3	5	4	5	4	154	124
Agilent	8494, 5, 6 H	5	5	4	4	4	1	5	5	3	5	4	5	4	169	139
Agilent	84904, 6, 7, K/L	5	5	4	4	4	1	5	2	3	5	4	5	4	160	139
Narda	DA series	5	2	2	3	2	5	2	2	3	4	2	4	2	170	89
Broadwave Technologies	651-031-063	1	5	2	2	4	5	2	2	3	4	2	5	2	177	96
SHX	GKTS	4	5	2	2	4	1	5	2	2	5	3	1	4	136	115
Trilithic	RPA	1	5	4	4	3	5	2	2	2	4	2	4	2	176	95
Trilithic	SPA	4	2	3	3	2	1	5	2	2	4	4	4	4	119	98
Aeroflex/Weinschel	3400 series	4	5	2	4	4	5	2	2	3	4	2	4	2	190	109
Aeroflex/Weinschel	3400T series	4	5	2	4	4	1	3	2	3	4	3	4	2	133	112
Aeroflex/Weinschel	150 series	5	5	3	4	4	4	3	2	3	4	4	4	2	188	122
Aeroflex/Weinschel	150T series	5	5	3	4	4	1	5	2	3	4	5	4	4	152	131
Aeroflex/Weinschel	4202, 3, 5	4	2	1	3	2	1	5	2	4	5	5	4	4	119	98
Aeroflex/Weinschel	4222 - 4248	4	1	1	3	5	1	5	2	4	4	5	4	4	126	105
JFW Industries	50P SS	1	3	5	3	2	1	5	2	3	5	5	4	4	123	102
JFW Industries	50P Relay	4	5	3	4	3	5	2	2	3	2	2	4	2	183	102

7.3.1 GigaBaudics

The PA13 by GigaBaudics employs solid state switching to achieve a large dynamic range of 0.065 db to 64 db. It has a very high bandwidth and low cut off frequency of DC-13 Ghz.

Figure 12: PA13

7.3.2 Mini-Circuits

The ZX73 by Mini-Circuits employs diode based switch system and has low bandwidth 2.5 Ghz BW and high low frequency cut-off of 10 Mhz.

7.3.3 Agilent

Agilent has a good selection of variable attenuators, all of which use solid state circuitry. They excel in almost all categories of measure and are one of the few that can be outfitted with SMA and N connectors. One disadvantage is that two units are required for attenuation step sizes below 10 db.

Figure 13: Agilent Solid State Variable Attenuator

7.3.4 Narda

Narda's DA series suffer from narrow bandwidth limits and high minimum insertion losses.

Figure 14: Narda DA series attenuator

7.3.5 Broadwave Technologies

Broadwave's model 651-031-063, is the highest frequency model that they make, which is still too low for our purposes at 2.2 Ghz

7.3.6 SHX

The GKTS series by SHX are relay controlled variable attenuators. Their specs result in a middle-of-the-road score.

Figure 15: SHX GKTS series attenuators

7.3.7 JFW Industries

JFW makes both solid state and relay series units as part of their 50P series. Their solid state version suffers from low bandwidth 3 Ghz and low minimum cutoff frequency. The relay version however scores well in the important categories.

Figure 16: JFW 50P series attenuators

7.3.8 Trilithic

Trilithic makes both solid state and relay series units as part of their RPA and SPA series. The relay based switcher has a low bandwidth of 3 Ghz and the solid state version has a high minimum insertion loss.

Figure 17: Trilithic RPA series attenuator

7.3.9 Aeroflex/Weinschel

Aeroflex makes a lot of good models both with relay and solid state switches. The 3400 series employ TO-5 relay can switches with a bandwidth of 6 Ghz. They score relatively highly in the attributes that most count.

Aeroflex makes a built-in microprocessor based version of the 3400, model 3400T. This would simplify design and reduce costs of implementation, but is incompatible with TB operations.

Aeroflex makes a solid state and non-solid state version of the 150 series, the 150 and 150T. The 150 version scores the highest, it can operate up to 26.5 GHz and utilizes reed switches. This is the only reed switch based variable attenuator in this study. Based on our reading these may be just as radiation resistant at relay switches, but this needs to be confirmed.

Aeroflex makes two other solid state digital control variable attenuators that are closely related, the 4202 (3,5) and 4222 (-48) series. These models provide large bandwidths, but high low frequency cut-offs.

Figure 18: Aeroflex variable attenuators

8. ORGANIZATIONAL IMPACT

Employment of the RAS will impact shot operations both on the shot-setup side and on the shot cycle operations side. Operations support for the installation of fixed attenuators into diagnostics will reduce and this may require a redeployment or reduction in operations staffing levels. Reductions in scheduled training will be required as setup procedures become obsolete. Procedures and qualifications cards will need to be updated to reflect this.

The influence to shot operations is less impactful unless an off-normal were to occur. This would trigger verification steps and troubleshooting procedures different from what would be used for fixed attenuators.

9. RISKS ASSESSMENT

A Failure Mode Effects Analysis was performed on the RAS and is shown in the table below. Significant risks lay in the area of mechanical failure, los of calibration, and improper shot setup. None of these risks relate to personal safety, only diagnostic malfunction and loss of shot data. Post mitigation, the most probable failure is improper shot setup, and this is do the human interface required for this task.

Table 8: RAS Failure Mode Effects Analysis

Failure Mode	Causes	Effects	Personnel Consequence before Mitigation[1]	Probability of Occurrence before Mitigation[2]	Mitigation	Personnel Consequence After Mitigation	Probability of Occurrence After Mitigation
List the failure mode.	Describe the cause. Use multiple rows for multiple causes.	Describe the effect(s) on the system in which the failure occurs.	Rate the severity of hazard to personnel before mitigation efforts are made.	Estimate the likelihood of the failure occurring before mitigation efforts are made.	Describe the step(s) necessary for mitigating the likelihood of the failure occurring.	Rate the severity of hazard to personnel after mitigation efforts have taken place.	Estimate the likelihood of the failure occurring after mitigation efforts have taken place.
Connector Failure	• Exceed cycle lifetime • Improper torque	• Loss of electrical connection • Poor electrical connection • Loss of shot data	None	Infrequent	• Use access requires procedure or system expert • Reduced number of planned maintenance cycles • Uses common standard connector types	None	Improbable
Loss of calibration	• Switch failure • Over voltage	• Loss of shot data • Mechanical damage • Improper impedance	None	Infrequent	• Pre shot dry-run checklist in place • Post shot analysis	None	Improbable
Improper impedance	• Incorrect CMT request • Incorrect ICCS control voltage	• Loss of shot data • Possible scope damage	None	Probable	• Pre shot dry-run checklist in place • Post shot analysis • CMT templates, and peer review • Comprehensive commissioning test plan, with IQ and OQ standards	None	Infrequent